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Avalanche Multiplication Characteristics of $Al_{0.8}Ga_{0.2}As$ Diodes

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***Abstract*—The avalanche multiplication characteristics of $Al_{0.8}Ga_{0.2}As$ have been investigated in a series of p-i-n and n-i-p diodes with i-region widths, w, varying from 1 μm to 0.025 μm. The electron ionization coefficient, α, is found to be consistently higher than the hole ionization coefficient, β, over the entire range of electric fields investigated. By contrast with $Al_xGa_{1-x}As$ ($x \leq 0.6$) a significant difference between the electron and hole initiated multiplication characteristics of very thin $Al_{0.8}Ga_{0.2}As$ diodes ($w = 0.025$ μm) was observed. Dead space effects in the diodes with $w \leq 0.1$ μm were found to reduce the multiplication at low bias below the values predicted from bulk ionization coefficients. Effective α and β that are independent of w have been deduced from measurements and are able to reproduce accurately the multiplication characteristics of diodes with $w \geq 0.1$ μm and breakdown voltages of all diodes with good accuracy. By performing a simple correction for the dead space, the multiplication characteristics of even thinner diodes were also predicted with reasonable accuracy.**

***Index Terms*—AlGaAs, APD, avalanche multiplication, avalanche photodiodes, ionization coefficients, impact ionization.**

I. Introduction

BECAUSE of its mature technology base and its ability to vary the material properties, such as band gap and refractive index via the aluminum composition while maintaining close lattice-match to GaAs, $Al_xGa_{1-x}As$ is widely used in semiconductor devices. In applications such as IMPATT diodes, heterojunction bipolar transistors (HBTs), and high electron mobility field effect transistors (HEMTs) an accurate knowledge of the avalanche characteristics of $Al_xGa_{1-x}As$ is required to obtain optimum power performance. While several experimental studies have been made of the impact ionization process in $Al_xGa_{1-x}As$, these were mainly limited to compositions $x \leq 0.6$ [1]–[11]. A recent investigation of the impact ionization process in bulk ($\sim$1 μm) $Al_{0.8}Ga_{0.2}As$ diodes [12] indicates that the electron and hole ionization coefficients, α and β respectively, differ significantly so that very low excess noise can be achieved. However, many semiconductor devices utilize high field regions which are much thinner. In these structures, the dead space, the minimum distance a carrier must travel before it gains sufficient energy to impact ionize, can become important [7], [8] and this nonlocal behavior can cause the multiplication characteristics of thin structures to deviate from bulk behavior. Knowledge of the nonlocal ionization behavior at high electric fields is therefore essential for modeling semiconductor devices incorporating $Al_{0.8}Ga_{0.2}As$.

In this work, we report on the impact ionization process in a series of $Al_{0.8}Ga_{0.2}As$ p-i-n and n-i-p diodes with nominal i-region thicknesses w ranging from 1 μm down to 0.025 μm over a wide range of electric field. The ionization coefficients for $Al_{0.8}Ga_{0.2}As$ over the electric field range from 328 kV/cm to 1540 kV/cm are deduced from these measurements. A simple correction of the dead space allows the ionization coefficients to be used to describe the multiplication process even in devices with $w < 0.1$ μm.

II. Experiment

A. Growth

The $Al_{0.8}Ga_{0.2}As$ p-i-n (n-i-p) diodes used in this study were grown by conventional solid-source molecular beam epitaxy on n^+ (p^+) (100) oriented GaAs substrates, similar to those reported previously [12]. The layers grown consist of five homojunction p-i-n/n-i-p structures and a heterojunction p-i-n structure. The nominal i-region thicknesses of the homojunction p-i-n and n-i-p structures are $w = 0.4$, 0.1, 0.05, 0.025 μm and $w = 0.1$ μm respectively while the heterojunction structure has $w = 0.8$ μm. The homojunction structures comprise a 0.25 μm n^+ (p^+) GaAs buffer, a 0.5 μm n^+ (p^+) $Al_{0.8}Ga_{0.2}As$ layer (1 μm for the $w = 0.1$ μm p-i-n), an undoped $Al_{0.8}Ga_{0.2}As$ i-region, a 1 μm p^+ (n^+) $Al_{0.8}Ga_{0.2}As$ layer and a thin 0.01 μm p^+ (n^+) GaAs cap. For the heterojunction p-i-n structure, a similar configuration is used except that a 0.5 μm n^+ GaAs layer replaces the 0.5 μm n^+ $Al_{0.8}Ga_{0.2}As$ layer to form a heterojunction at the i-n interface. The p^+ and n^+ layers of all structures were highly doped with Be and Si respectively to levels of $\sim 2 \times 10^{18}$ cm^{-3}.

Double crystal X-ray rocking curves were used to verify the aluminum composition of each layer. Standard lithography and wet chemical etching were used to fabricate 100–400 μm diameter circular mesa diodes with annular ohmic contacts for top optical access. Etched windows directly below the homojunction diodes were formed by selectively reactive ion etching the substrate to the n^+ (p^+) cladding layers for all except the $w = 0.4$ μm and $w = 0.05$ μm p-i-n structures. These provide optical access to the back of the p-i-n (n-i-p) diodes so that multiplication characteristics under pure electron and pure hole injection conditions can be obtained from the same diode.

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TABLE I
MEASURED AND MODELED PARAMETERS OF THE $Al_{0.8}Ga_{0.2}As$ DIODES

Layer No.	Diode type	Nominal i-region thickness (μm)	Breakdown Voltage V_{bd} (V)		Modeled results		
			Measured	Predicted	Cladding doping p = n ($\times10^{18}$ cm^{-3})	i-region doping ($\times10^{15}$ cm^{-3})	i-region thickness, w (μm)
P1	PIN	1.0	53.6	53.6	1.40	0.48	1.024
P2	PIN	0.8	44.2	44.5	1.20	1.10	0.815
P3	PIN	0.4	21.5	22.0	0.85	8.50	0.312
P4	PIN	0.1	14.0	14.0	0.625	1.00	0.100
P5	PIN	0.05	9.1	8.5	1.65	0.50	0.032
P6	PIN	0.025	8.8	8.3	1.64	6.00	0.015
N1	NIP	1.0	52.6	52.9	1.64	0.51	1.011
N2	NIP	0.1	10.8	10.3	1.60	9.50	0.088

B. Electrical Characterization

Capacitance–voltage (C–V) measurements were performed on each layer using a multifrequency LCR meter. The characteristics were modeled by solving Poisson's equation with the depletion approximation to determine the p^+, n^+ and i-region doping levels and the i-region thickness of each structure. Secondary ion mass spectroscopy (SIMS) measurements were also performed on selected layers to verify the parameters extracted from *C–V* modeling.

Dark current–voltage (*I–V*) measurements were carried out using a source measure unit. The forward *I–V* measurements indicate that all layers have a low turn-on voltage and negligible series resistance over the current range measured. Reverse *I–V* measurements revealed a sharp and well-defined breakdowns. At the breakdown voltage V_{bd} the reverse current was observed to increase by several orders of magnitude for a small change in reverse voltage.

C. Photomultiplication Measurements

Photomultiplication measurements [13] were carried out using 442, 542, and 633 nm light. The light was focused to a small spot ($\sim$10 μm) on either the top or back cladding of the homojunction diodes to inject carriers into the high field regions. DC photocurrent was measured as a function of bias to deduce the multiplication characteristics. AC measurements were also taken using a lock-in amplifier with the light modulated at $\sim$180 Hz. This phase-sensitive detection technique ensures that only the photocurrent was measured and rejects leakage currents. The multiplication characteristics from both dc and ac measurements were found to be identical in all layers. Photomultiplication values were also verified to be independent of the excitation light intensity over the range of current used. Gain uniformity of each layer was confirmed by identical multiplication characteristics measured with the excitation light illuminating different parts of the optical access window of a diode and on several diodes across the wafer. The heavily doped cladding layers in the homojunction diodes ensured that widening of the depletion region with reverse bias is small and the corresponding increase in primary photocurrent (typically $<$2%) prior to the onset of multiplication was corrected using the procedure described by Woods *et al.* [14]. Multiplication values of at least 20 (in excess of 100 in some cases) were measured on most of the diodes investigated.

Pure electron (hole) initiated multiplication characteristics, $M_e(M_h)$, were obtained for the homojunction diodes by illuminating the p^+ (n^+) cladding with 442 nm light, since approximately 99.7% (95%) of the light is absorbed in a 1 μm (0.5 μm) thick $Al_{0.8}Ga_{0.2}As$ layer. 542 nm light was also used to investigate the multiplication characteristics, M_{mixed}, of the diodes under mixed carrier injection condition. Since the optical absorption coefficients of $Al_{0.8}Ga_{0.2}As$ at 542 nm wavelength [15] is only about 574 cm^{-1}, this light is only weakly absorbed and photocarriers are created almost uniformly throughout the high-field region. In the case of the heterojunction p-i-n structure, M_e was measured in a manner identical to that for the homojunction diodes, where the top cladding is illuminated with 442 nm light. To measure M_h, 633 nm light was used instead to illuminate the n^+ GaAs back cladding. In contrast to the homojunction diodes, holes can be injected into the high field region via top illumination of the heterojunction diodes with 633 nm light, since this wavelength is beyond the absorption edge of $Al_{0.8}Ga_{0.2}As$ [15]. To confirm the M_h results, the measurements were also repeated using 820 nm light to illuminate the n^+ GaAs cladding. M_h characteristics measured with 633 nm and 820 nm light were identical, suggesting that pure hole injection condition was achieved in both cases.

III. RESULTS

The results deduced from the *C–V* profile of each layer are summarized in Table I. The parameters extracted from *C–V* modeling gave good agreement with the results from SIMS measurements. For completeness, two previously reported layers [12], P1 and N1, are also included in Table I. Fig. 1 illustrates the typical dark current characteristics of P2, P6, and N2, respectively. The dark currents for all layers are typically $<$1 nA for a 200 μm diameter diode at 95% V_{bd}. Although layers P5 and P6 have very thin multiplication regions, only a small increase in dark current near V_{bd} due to tunneling was seen. This behavior contrasts with that seen in similar

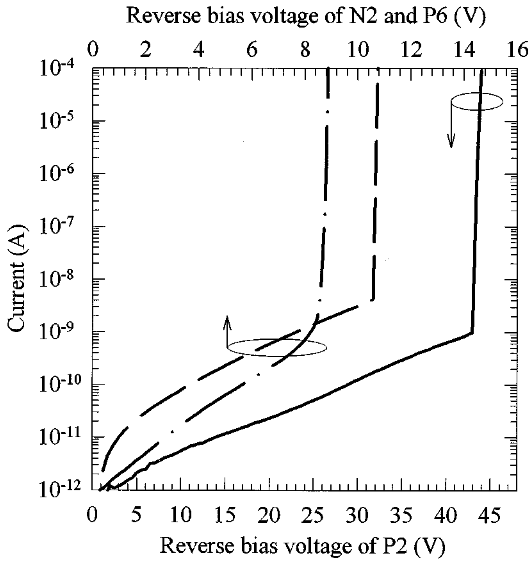

Fig. 1. Typical dark current characteristics of P2 (solid line), N2 (dashed line), and P6 (dot-dashed line).

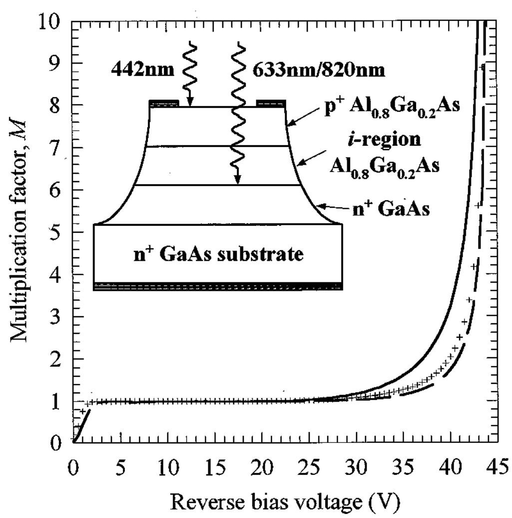

Fig. 2. Multiplication versus bias of P2 with M_e (solid line) and M_h (dashed line) obtained by top illuminating the diodes with 442 nm and 633 nm (820 nm) light, respectively. M_{mixed} (+) obtained using 542 nm light lies between M_e and M_h. Inset shows a schematic view of the heterojunction diode.

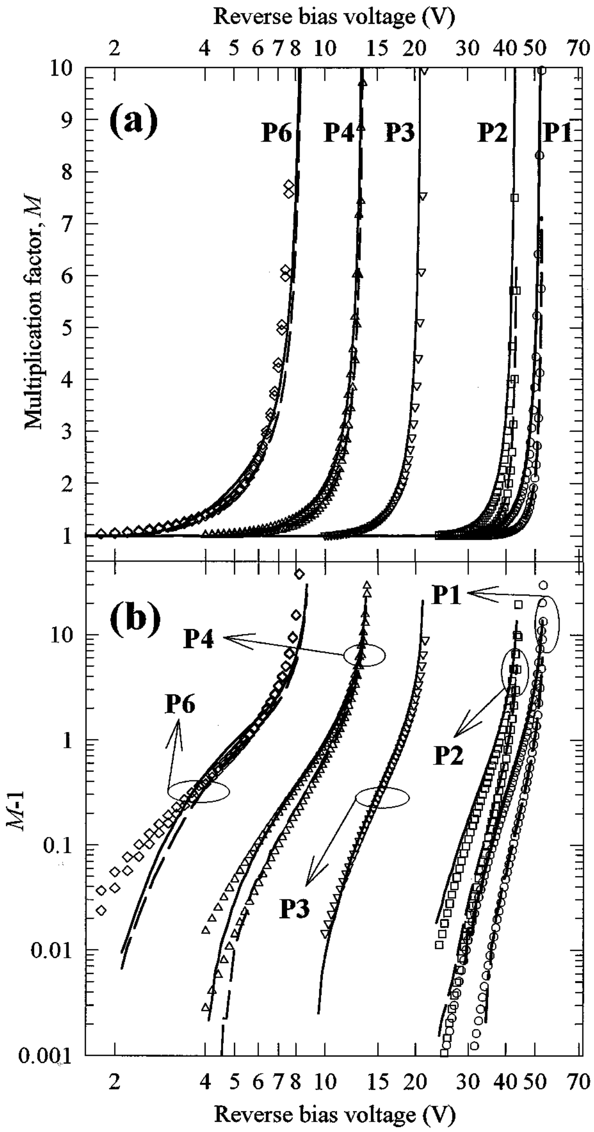

Fig. 3. M_e (solid lines) and M_h (dashed lines) from the p-i-n diodes investigated. The symbols represent results from modeling. M_{mixed} (not shown) were found to lie between M_e and M_h, as expected.

thicknesses of GaAs [7] and is due to the larger band gap in $Al_{0.8}Ga_{0.2}As$.

Fig. 2 depicts the multiplication characteristics of P2 under illumination at different wavelengths. M_e is larger than M_h, indicating that $\alpha > \beta$. M_{mixed} from 542 nm light lies between M_e and M_h, as expected. However, since the absorption coefficient of GaAs is two orders of magnitude higher than $Al_{0.8}Ga_{0.2}As$ at the wavelength of 542 nm [15], most of the 542 nm light is absorbed in the n^+ GaAs cladding layer. Consequently, the carriers injected into the high field region are predominately holes from the n^+ GaAs cladding and M_{mixed} is closer to M_h. The steps observed in M_h and M_{mixed} are attributed to the trapping of holes at the i-n hetero-interface at low bias.

Figs. 3(a) and 4(a) show the multiplication characteristics of all of the p-i-n and n-i-p diodes respectively under different carrier injection conditions. These characteristics are also plotted as $(M-1)$ on a logarithmic scale in Figs. 3(b) and 4(b) to emphasize the low multiplication values. Reliable multiplication values as low as 1.001 were measured, as seen from the $(M-1)$ plots. For clarity, M_e for P5 is plotted together with the n-i-p diodes in Fig. 4. M_e is found to be consistently larger than M_h for all p-i-n diodes investigated, although M_e and M_h converge as w decreases from 1 μm down to 0.025 μm. M_{mixed} for all layers (not shown) also lies between M_e and M_h, corroborating $\alpha > \beta$. Similarly, the n-i-p diodes exhibit multiplication characteristics that mirror those of the p-i-n diodes, as illustrated in Fig. 4. The multiplication characteristics were also fitted using Miller's empirical multiplication equation [16] to estimate V_{bd} for each layer. The values extracted are in close agreement with those obtained from reverse dark *I–V* measurements and are listed in Table I.

M_e and M_h for $Al_xGa_{1-x}As$ ($x \leq 0.6$) have been found to converge in thinner structures and become indistinguishable for $w \leq 0.05$ μm [7]–[10]. By contrast, there remains an appre-

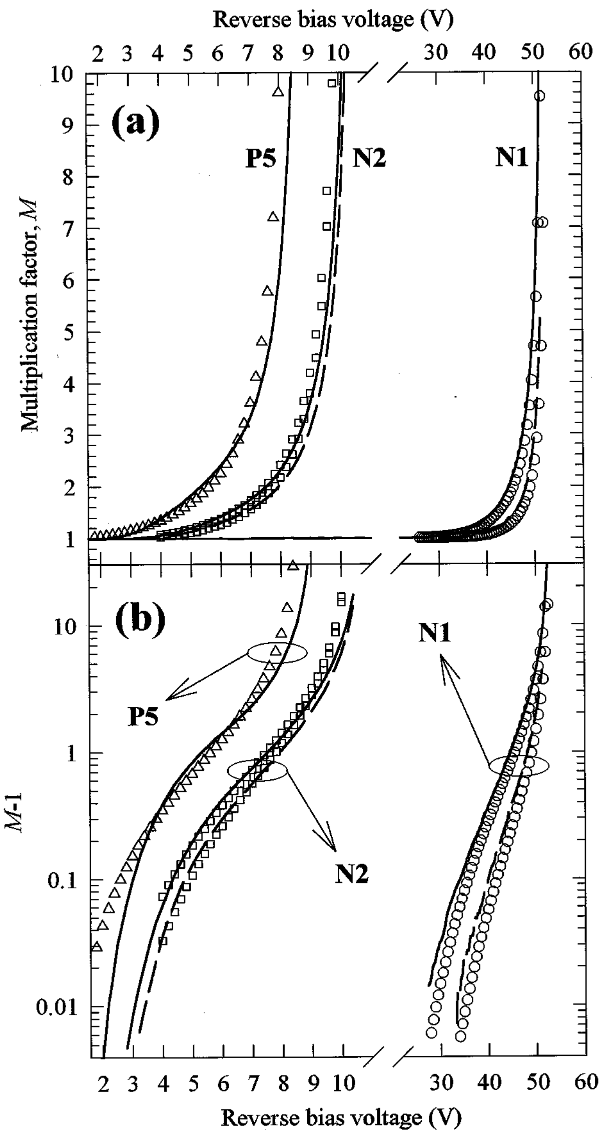

Fig. 4. M_e (solid lines) and M_h (dashed lines) of the homojunction n-i-p diodes, N1 and N2, and the homojunction p-i-n structure, P5 ($w = 0.05$ μm). The symbols represent results from modeling. M_{mixed} (not shown) were also found to lie between M_e and M_h.

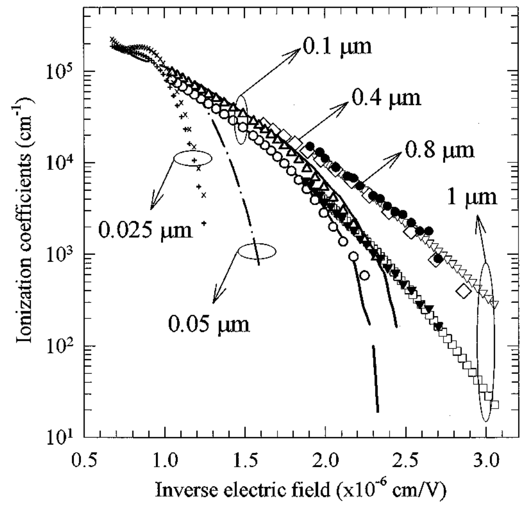

Fig. 5. Ionization coefficients extracted from M_e and/or M_h for P2 $\{\alpha(\bullet), \beta(\blacktriangledown)\}$, P3 $\{\alpha = \beta(\Diamond)\}$, P4 $\{\alpha$ (solid line), β(dashed line)$\}$, P5 $\{\alpha = \beta$(dot-dashed line)$\}$, P6 $\{\alpha(\times), \beta(+)\}$ and N2 $\{\alpha(\triangle), \beta(\bigcirc)\}$ using the conventional local interpretation. P1 and N1 have been analyzed previously and their ionization coefficients are represented by the parameterized $\alpha(\triangledown)$ and $\beta(\square)$ from [12]. The numbers represent the nominal value of w.

ciable difference between M_e and M_h in sample P6 (see Fig. 3) even though w has become extremely thin.

IV. Discussion

Effective ionization coefficients were extracted from the multiplication characteristics using the equations from the conventional local model [13]

$$M_e = \frac{1}{1 - \int_0^{w_T} \left[\alpha(x) \exp\left(-\int_0^x (\alpha(x) - \beta(x))\, dx'\right)\right] dx} \tag{1}$$

and

$$M_h = \frac{1}{1 - \int_0^{w_T} \left[\beta(x) \exp\left(\int_x^{w_T} (\alpha(x) - \beta(x))\, dx'\right)\right] dx} \tag{2}$$

where w_T is the total depletion width at the respective bias. The technique described by Grant [17] was used to allow for the nonuniform electric field profiles which were calculated from the parameters in Table I. The resulting α and β are plotted against inverse electric field in Fig. 5. Since the ionization coefficients of P1 and N1 have been analyzed previously, they are represented by the parameterized values of [12] in Fig. 5. As M_h was not measured for P3 and P5, the effective ionization coefficients of these layers are extracted assuming $\alpha = \beta$. At low values of M_e, α is relatively insensitive to the values of M_h [18]. Consequently, these coefficients will approximate to its true effective α at low multiplication values.

There is good agreement between the ionization coefficients extracted from P2 and those of P1 and N1. This indicates that a heterojunction structure may be used to measure M_e and M_h from the same diode. The effective α of P3 agrees with that of P1 and only deviates very slightly at the lowest electric field values in P3. Since this deviation is very small, it can be concluded that dead space is at most marginal in this structure.

In diodes with $w \leq 0.1$ μm, however, both the effective electron and hole ionization coefficients are seen to fall significantly below the bulk values of P1 and N1 at low fields and this effect becomes more pronounced as w decreases. On the other hand, these effective ionization coefficients are found to converge to the extrapolated bulk values at high electric fields. This behavior has also been observed in other thin $Al_xGa_{1-x}As$ ($x \leq 0.6$) structures [7]–[10] and can be interpreted qualitatively as follow. In thick avalanche structure, the dead space is only a small fraction of the high field region width. As the width decreases, the dead space becomes a significant fraction of w. Carrier ionization can only occur in the remaining fraction of w and the multiplication values are lower than expected at low electric fields. This causes the deduced effective ionization coefficients of thin structures to fall appreciably below the bulk values. As the field is increased the dead space decreases, reducing its effect on multiplication and the effective ionization coefficients rise rapidly to the bulk values. In spite of the fact that electrons and holes normally have different threshold energy and hence might be expected to have different dead spaces, the results here suggest that the magnitude of the dead space for electrons and holes is very similar.

The effective $\alpha(=\beta)$ of P5 at high fields appears to deviate from the bulk value. This behavior is more obvious in P6, where the effective α and β are seen to overshoot the bulk values at high fields. In addition, α in P6 first converges to β before deviating again at the highest fields. This anomaly could be due to the nonequilibrium impact ionization process at these high fields and short w, so that interpretation using the local model is no longer even approximately valid in this highly nonlocal regime.

A rigorous analysis by Plimmer *et al.* [9] has demonstrated that effective ionization coefficients, independent of w, can be used to characterize the avalanche process in semiconductors within the framework of the local model. Despite the simplicity of this technique, it was shown that these effective ionization coefficients were able to predict multiplication characteristics of the entire range of p-i-n structures with $w \geq 0.1$ μm, and that the high M values and breakdown voltages were also accurately predicted for even thinner structures. To investigate this, effective ionization coefficients that depend only on electric field, F, are obtained from the results in Fig. 5 by parameterizing the fit to the high field sections of the effective ionization coefficients of each structure. These effective ionization coefficients extend the electric field range of our previous results [12] to 328 kV/cm $\leq F \leq$ 1540 kV/cm and can be expressed as

$$\alpha = 3.18 \times 10^5 \exp\left[-\left(\frac{1.04 \times 10^6}{F}\right)^{1.67}\right] \text{ cm}^{-1} \quad (3)$$

$$\beta = 3.55 \times 10^5 \exp\left[-\left(\frac{1.12 \times 10^6}{F}\right)^{1.85}\right] \text{ cm}^{-1} \quad (4)$$

for 328 kV/cm $\leq F < 1110$ kV/cm and

$$\alpha = \beta = 3.84 \times 10^6 \exp\left[-\left(\frac{1.02 \times 10^7}{F}\right)^{0.55}\right] \text{ cm}^{-1} \quad (5)$$

for 1110 kV/cm $\leq F \leq 1540$ kV/cm.

To test these new parameterized data, M_e and M_h for all diodes were calculated using (1) and (2), taking into account the electric field profiles, and the parameterized form of the effective coefficients in (3)–(5). Excellent agreement is found with the measured data for all device thicknesses with $w \geq 0.1$ μm. For P4 with $w = 0.1$ μm, agreement with multiplication values of $M < \sim 2$ is poor. The calculated results for the two thinnest structures (P5 and P6) deviate significantly from the measured M at all values.

Okuto *et al.* [19] found excellent agreement with experimental results by accounting for the dead space in the local model using

$$\alpha(x) = 0 \quad \text{for} \quad 0 \leq x < x_n \quad (6)$$

$$\beta(x) = 0 \quad \text{for} \quad w_{\mathrm{T}} - x_p \leq x < w_{\mathrm{T}} \quad (7)$$

where x_n and x_p are the electron and hole dead spaces, respectively, obtained from the threshold energy, E_{th}, associated with impact ionization

$$E_{th} = \int_0^{x_n} F(x)\,dx = \int_{w_{\mathrm{T}}-x_p}^{w_{\mathrm{T}}} F(x)\,dx. \quad (8)$$

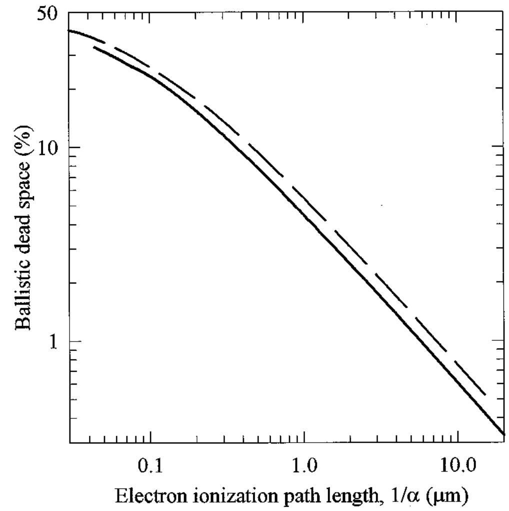

Fig. 6. Ballistic dead space of GaAs (dashed line) and $Al_{0.8}Ga_{0.2}As$ (solid line) plotted against the electron ionization path length, $1/\alpha$. The ballistic dead space is calculated using the average energy gap value [21] as the threshold energy, and is expressed as a percentage of the ionization path length.

Bulman *et al.* [4] and Flitcroft *et al.* [20] have also reported that good agreement with the experimental results were achieved when similar techniques are used to correct for the dead space effect.

The calculations were repeated for all structures incorporating the simple correction of Okuto *et al.* [19], (6)–(8), in (1) and (2) of the local model. E_{th} was taken as the average band gap (= 2.23 eV) [21] of $Al_{0.8}Ga_{0.2}As$. While the agreement for the thicker structures is not altered, the agreement with the thinner structures P4, P5 and P6 is improved when this correction is taken into account. The lower multiplication values of P4 is predicted with good accuracy down to $M = \sim 1.1$ (Fig. 3). In the case of P5 and P6, there is now reasonable agreement for $M > \sim 1.3$ (see Figs. 3 and 4). The breakdown voltages predicted using the new parameterized ionization coefficients agreed with the measured values of all diodes to within a few percent and are listed in Table I for comparison.

The dead space effect on multiplication was found to be important only in p-i-n/n-i-p $Al_xGa_{1-x}As$ ($x \leq 0.6$) diodes with $w \leq 0.1$ μm. Our results may, at first sight, appear surprising, since dead space increases with threshold energy, which generally increases with energy gap. Thus, as x (and consequently the energy gap) in $Al_xGa_{1-x}As$ increases, one might expect dead space effects to become important in increasingly thicker structures. However, measurements show that the value of w at which dead space becomes important is independent of x [7]–[10]. The reason for this becomes clear when we plot the ballistic dead space, $d = E_{th}/qF$, against the mean ionization path length ($1/\alpha$) of electrons for GaAs and $Al_{0.8}Ga_{0.2}As$, as depicted in Fig. 6. The ionization coefficients of GaAs are taken from the work by Bulman *et al.* [4] and Millidge *et al.* [6]. E_{th} for GaAs is taken as 1.75 eV, following [21]. For comparison, the dead space has been expressed as a fraction of the respective $1/\alpha$ values. It is apparent from Fig. 6 that the dead spaces of both

GaAs and $Al_{0.8}Ga_{0.2}As$ are a similar fraction, within experimental errors, of ionization path length. The relative increase in threshold energy (and hence in dead space) is offset by the increase in electric field required to obtain a given ionization in $Al_{0.8}Ga_{0.2}As$. This is also found to be true for the other aluminum compositions ($x \leq 0.8$). The result explains why, for a given value of multiplication, a short $Al_xGa_{1-x}As$ structure of a given w will experience the same dead space effect, independent of x (for $x \leq 0.8$).

V. Conclusion

The avalanche multiplication characteristics of $Al_{0.8}Ga_{0.2}As$ have been measured accurately in a series of p-i-n/n-i-p diodes. The α/β ratio is large at low fields but decreases to almost unity at high electric fields. As in $Al_xGa_{1-x}As$ ($x \leq 0.6$), the dead space effect is found to reduce the low field multiplication values of diodes with $w \leq 0.1$ μm, so that the effective α and β are lower than the bulk values. As the field increases in these diodes, the effective α and β rise rapidly and approach the bulk values. New effective values of α and β, independent of w, were deduced and parameterized from these results over the electric field range of 328–1540 kV/cm. The multiplication characteristics predicted using these ionization coefficients and the local model are shown to give good agreement with measured multiplication values for diodes with $w \geq 0.1$ μm. By performing a simple correction for the dead space in the local model, reasonable agreement is also obtained for diodes with $w \leq 0.05$ μm. In addition, the breakdown voltages of all diodes are accurately predicted by these effective ionization coefficients.

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